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TWO-DIMENSIONAL WIND-TUNNEL INVESTIGATION OF TWO NACA LOW-DRAG AIRFOIL SECTIONS EQUIPPED WITH SLOTTED FLAPS AND A PLAIN NACA LOW-DRAG AIRFOIL SECTION FOR XF6U-1 AIRPLANE

By Lawrence K. Loftin, Jr., and Fred J. Rice, Jr.

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NACA

WASHINGTON

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NACA LANGLEY MEMORIAL AERONAUTICAL LABORATORY

MEMORANDUM REPORT

for the

Bureau of Aeronautics, Navy Department

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TWO-DIMENSIONAL WIND-TUNNEL INVESTIGATION OF TWO NACA LOW-DRAG AIRFOIL SECTIONS EQUIPPED WITH SLOTTED FLAPS AND A PLAIN NACA LOW-DRAG AIRFOIL SECTION FOR XF6U-1 AIRPLANE

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SUMMARY

A two-dimensional wind-tunnel investigation was conducted to determine the aerodynamic characteristics of the NACA 65(215)-114 airfoil (root section), the NACA 65_1-212, a = 0.6, airfoil (tip section), and an intermediate airfoil section of the Chance-Vought XF6U-1 airplane. The root and intermediate airfoil sections were equipped with 25.92-percent airfoil-chord and 33.62-percent airfoil-chord slotted flaps. The optimum angular flap deflection for maximum lift was found to be 40° and maximum lift coefficients corresponding to this deflection were 2.63 and 2.80 for the root and intermediate sections at a Reynolds number of 9×10^6. The use of a 4° cruising flap deflection caused the lift coefficient corresponding to the upper limit of the low-drag range to increase from 0.3 to 0.4 for the root section and from 0.35 to 0.5 for the intermediate section, both at a Reynolds number of 9×10^6. On both airfoils the increment in minimum drag coefficient caused by the 4° flap deflection was approximately 0.001 at a Reynolds number of 9.0×10^6.

INTRODUCTION

At the request of the Bureau of Aeronautics, Navy Department, tests were conducted in the Langley two-dimensional, low-turbulence tunnels of three 24-inch-chord airfoil models representing the root and tip airfoil sections and an intermediate airfoil section of the proposed Chance-Vought XF6U-1 airplane. The airfoils tested were the NACA $65_{(215)}$-114 (root section), the NACA 65_1-212, a = 0.6 (tip section), and an intermediate section taken at approximately 55 percent of the semi-span. The models of the root and intermediate sections were equipped with slotted flaps.

The tests included the determination of the aerodynamic characteristics of the three plain airfoil sections in both the smooth condition and with standard roughness applied to the leading edge. Lift tests of the root and intermediate airfoil sections were made for a range of flap deflections extending from 0° to 50°. Most of the data were obtained at a Reynolds number of 9×10^6 although comparison tests were conducted at Reynolds numbers of 1×10^6, 3×10^6, and 6×10^6.

COEFFICIENTS AND SYMBOLS

c	basic airfoil chord with flap retracted and neutral
q	free-stream dynamic pressure
l	airfoil section lift
d	airfoil section drag
$m_{c/4}$	airfoil section quarter-chord pitching moment
c_l	airfoil section lift coefficient, $\frac{l}{qc}$
$c_{l_{max}}$	maximum airfoil section lift coefficient, $\frac{l_{max}}{qc}$
c_d	airfoil section drag coefficient, $\frac{d}{qc}$

$c_{m_{c/4}}$ airfoil section quarter-chord pitching-moment coefficient, $\frac{m_{c/4}}{qc^2}$

$c_{m_{a.c.}}$ airfoil section pitching-moment coefficient about the aerodynamic center, $\frac{m_{a.c.}}{qc^2}$

α_o airfoil section angle of attack

δ flap deflection with respect to airfoil chord

R airfoil section Reynolds number

MODELS

The airfoil sections for which data were desired consisted of the NACA $65_{(215)}$-114 (root section), the NACA 65_1-212, a = 0.6 (tip section), and an intermediate airfoil section taken at approximately 55 percent of the semispan. The root and intermediate airfoil sections were equipped with slotted flaps of 25.92- and 33.62-percent airfoil chord, respectively. The resulting chord sizes correspond to a flap of constant chord length on the three-dimensional wing. With the flaps in the retracted position, the airfoil slot lip was located at 0.9150c and 0.8892c on the root and intermediate airfoil sections, respectively.

The 24-inch-chord models of the three airfoil sections tested were constructed of laminated mahogany. The surfaces were then painted and sanded with number 400 carborundum paper to produce an aerodynamically smooth finish. Ordinates of the three airfoil sections are presented in tables I, II, and III. The flaps were cut from dural and were finished in a manner similar to that described for the plain airfoil models. Drawings of the root and intermediate airfoils sections with flap deflected are presented in figures 1 and 2 together with the flap ordinates and the dimensions locating the flap at the prescribed positions corresponding to the angular deflections tested. The flap paths used were designated by the Chance-Vought Corporation. A drawing of the tip section is shown in figure 3.

TESTS

The tests of the three airfoil models were conducted in the Langley two-dimensional low-turbulence pressure tunnel (designated TDT) and the Langley two-dimensional low-turbulence tunnel (designated LTT). Both of these tunnels have test sections which measure 3 feet by 7.5 feet; the models, when mounted, completely span the 3-foot dimension with the junction between the model and tunnel walls sealed. Lift measurements were obtained by integrating the pressure reaction on the floor and ceiling of the tunnel. Drag coefficients were determined by the wake-survey method, and the quarter-chord pitching-moment coefficients were measured with a torque balance. All coefficients were calculated using the basic airfoil chord with flap retracted and neutral. A more complete description of these tunnels and the methods employed for obtaining and reducing the experimental data is contained in reference 1. The following formulas derived from reference 1 were used to correct the tunnel data to free-air conditions:

$$c_l = 0.976c_l'$$

$$c_d = 0.991c_d'$$

$$q = 1.0594q'$$

$$\alpha_o = 1.015\alpha_o'$$

Lift and drag results were obtained for the three plain airfoil sections in the smooth condition at Reynolds numbers of 1×10^6, 3×10^6, 6×10^6 and 9×10^6. Lift and drag were also measured at a Reynolds number of 6×10^6 with standard roughness (reference 1) applied to the leading edge of the model. The pitching-moment characteristics of the three models in the smooth condition were determined at Reynolds numbers of 3×10^6, 6×10^6, and 9×10^6.

Lift results were obtained for the root and intermediate airfoil sections in the smooth condition through a range of flap deflections extending from 0° to 50°.

The lift characteristics of these two airfoils were also determined with the flap fully extended but not deflected, and with the flap partially extended and deflected 4°. The latter configuration was intended to be used as a cruising deflection for the full-scale airplane. The Reynolds number of most of these tests was 9×10^6; however, the effect of increasing the Reynolds number from 1×10^6 to 9×10^6 was determined for the airfoils with 40° flap deflection, 0° full extended configuration, and 4° cruise condition. Tests were also made at a Reynolds number of 6×10^6 with the flap deflected 40° and standard roughness applied to the leading edge.

Pitching-moment characteristics were determined for both models at flap deflections of 4° and 40°. The Reynolds number of the tests was 6×10^6 with the flap deflected 40° and 9×10^6 for the 4° deflection.

Drag results were obtained for only one flap deflection, the 4° (partially extended) cruise configuration. The data were obtained at Reynolds numbers of 1×10^6 and 9×10^6.

RESULTS AND DISCUSSION

Flap retracted.- The results of tests of the three plain airfoil sections are presented in figures 4, 5, and 6. A comparison of these results indicates that at a Reynolds number of 9×10^6 all three sections have approximately the same maximum lift coefficient. Decreasing the Reynolds number from 9×10^6 to 3×10^6 appears to cause a decrement in maximum lift coefficient of about 0.1 for the intermediate and tip sections, and 0.05 for the root section. A further decrease in Reynolds number from 3×10^6 to 1×10^6 results in a decrement of approximately 0.35 in the maximum lift coefficient for all three sections. It is interesting to note that the maximum lift coefficients of the smooth sections at a Reynolds number of 1×10^6 is of the same order of magnitude as those obtained at a Reynolds number of 6×10^6 with standard roughness applied to the airfoil leading edge.

The minimum drag coefficient of the three smooth sections is seen to be approximately 0.0040 at a Reynolds number of 9×10^6. As the Reynolds number decreases from 9×10^6 to 3×10^6, the minimum drag coefficient increases by an increment of approximately 0.0010 for the root and intermediate sections and 0.0005 for the tip section. The most adverse effect of decreasing Reynolds number is, however, evident outside the range of lift coefficients corresponding to low-drag. Decreasing the Reynolds number to 1×10^6 results in a further increase in drag, with the most pronounced increase again appearing outside the low-drag range of lift coefficients. The low-drag range increases somewhat with decreasing Reynold number and, as might be expected, is slightly smaller for the tip section than for the root and intermediate sections. The minimum drag coefficient is approximately 0.0098 for all three sections in the rough condition; however, the drag increase with lift coefficient is more severe for the tip and intermediate sections than for the root section.

Flap deflected.- The lift characteristics corresponding to a Reynolds number of 9×10^6 and a range of flap deflections extending from 0° to 50° are presented in figures 7 and 8 for the root and intermediate airfoil sections. In order to facilitate analysis, the values of the maximum lift coefficients presented in figures 7 and 8 have been replotted in figure 9 as a function of flap deflection. The values of the maximum lift coefficient obtained with the 0° (full extended) and 4° (partially extended) flap configuration have not been included in this figure. The data shown in figure 9 indicate that the deflection for highest maximum lift coefficient is approximately 40° for both airfoil sections. The intermediate airfoil section has a maximum lift coefficient at a flap deflection of 40°, approximately 0.17 higher than the value 2.63 obtained for the root section. The higher maximum lift coefficient of the intermediate airfoil section probably results from the greater flap chord employed with this section. These values of the maximum lift coefficient are considerably better than the value 2.36 obtained with a 0.20c simulated split flap deflected 60° which was tested with these same two airfoil sections, but are less than the value 3.00 obtained with a 6-series airfoil section of approximately 14-percent thickness having a double-slotted flap (reference 2).

A comparison of the results presented in figures 7 and 8 shows that the maximum lift coefficient corresponding to the 4° (partially extended) "cruise" deflection is approximately 0.1 lower than that obtained for the 0° (full extended) configuration on both the root and intermediate airfoil sections. The results presented in figures 7 and 8 also show that extending the flap causes an increase in lift-curve slope over that of the plain airfoil. The use of the plain airfoil chord length in the determination of all lift coefficients causes this apparent increase in lift-curve slope.

The results of tests of the root and intermediate airfoil sections with 40° flap deflection are presented in figures 10 and 11 for Reynolds numbers of 1×10^6, 3×10^6, 6×10^6, and 9×10^6, and for a Reynolds number of 6×10^6 with standard roughness applied to the airfoil leading edge. Included also in these figures are the data obtained at Reynolds numbers of 1×10^6 and 9×10^6 for the 4° (partially extended) flap deflection and the 0° (full extended) flap configuration. The maximum lift coefficient obtained with the 40° flap deflection appears to suffer little as the Reynolds number is decreased from 9×10^6 to 3×10^6; however, decreasing the Reynolds number from 3×10^6 to 1×10^6 results in a decrement in maximum lift coefficient of approximately 0.32 for the intermediate section and 0.47 for the root section. The decrement in maximum lift coefficient on both plain airfoils for a decrease in Reynolds number from 3×10^6 to 1×10^6 was of the order of 0.35. As has been noted in tests of an airfoil equipped with a double-slotted flap (reference 2), the angle of zero lift decreases with decreasing Reynolds number.

For the root and intermediate sections, the decrements in maximum lift coefficient resulting from standard leading-edge roughness are 0.06 more and 0.13 less, respectively, for the airfoils with 40° flap deflection than for the plain airfoil. This result seems to agree with the data presented in reference 2 which shows that for an airfoil approximately 14-percent thick equipped with a double-slotted flap the decrement in maximum lift coefficient resulting as a consequence of standard roughness is approximately the same for the plain airfoil as for the airfoil with flap deflected. As was noted with the plain airfoils, the maximum lift coefficients of the smooth sections at a Reynolds number of 1×10^6 are nearly the same as those obtained at a Reynolds number of 6×10^6 with standard leading-edge roughness.

Drag data corresponding to Reynolds numbers of 1×10^6 and 9×10^6 are presented in figure 12 for the root and intermediate airfoil sections with the 4° (partially extended) flap deflection. Comparison of these data with those obtained for the plain airfoil shows that the flap causes an increment in minimum drag coefficient of approximately 0.0010 at a Reynolds number of 9×10^6 on both sections. At this same Reynolds number, the use of the 4° flap deflection caused the lift coefficient corresponding to the upper limit of the low-drag range to increase from 0.3 to 0.4 for the root section and from 0.35 to 0.5 for the intermediate section.

The pitching-moment characteristics of the two airfoils with flap deflections of 4° (partially extended) and 40° are presented in figure 13. A comparison of these data with those in reference 2 for a 6-series airfoil equipped with a double-slotted flap indicates that for lift coefficients up to the stall the pitching-moment coefficients are considerably less for the airfoil with the slotted flap.

CONCLUSIONS

The results of a two-dimensional wind-tunnel investigation of two NACA 65-series airfoil sections of approximately 14- and 13-percent thickness and equipped with 25.92-percent airfoil chord and 33.62-percent airfoil chord slotted flaps, respectively, and a plain airfoil section indicate the following conclusions:

1. The optimum flap deflection for maximum section lift coefficient was 40° for both of the airfoil sections equipped with slotted flaps.

2. The highest values of the maximum section lift coefficient obtained were 2.63 for the 14-percent thick airfoil section with the 25.92-percent airfoil-chord slotted flap, and 2.80 for the approximately 13-percent-thick airfoil section with the 33.62-percent airfoil-chord slotted flap.

3. At a Reynolds number of 9×10^6 the use of a 4° cruising flap deflection caused the lift coefficient corresponding to the upper limit of the low-drag range to increase from 0.3 to 0.4 for the root section and from 0.35 to 0.5 for the intermediate section. On both airfoils the increment in minimum drag coefficient caused by the 4° flap deflection was approximately 0.001 at a Reynolds number of 9.0×10^6.

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REFERENCES

1. Abbott, Ira H., von Doenhoff, Albert E., and Stivers, Louis S., Jr.: Summary of Airfoil Data. NACA ACR No. L5C05, 1945.

2. Braslow, Albert L., and Loftin, Laurence K., Jr.: Two-Dimensional Wind-Tunnel Investigation of an Approximately 14-Percent Thick NACA 66-Series-Type Airfoil Section with a Double-Slotted Flap. NACA TN No. 1110, 1946.

TABLE I

ORDINATES OF THE NACA $65_{(215)}$-114 AIRFOIL
(ROOT SECTION)

[Stations and ordinates given in percent of airfoil chord. Ordinates measured from airfoil chord line]

Upper Surface		Lower Surface	
Station	Ordinate	Station	Ordinate
0	0	0	0
.456	1.073	.544	-1.031
.701	1.300	.799	-1.230
1.195	1.642	1.305	-1.534
2.437	2.261	2.563	-2.075
4.929	3.186	5.071	-2.870
7.426	3.906	7.574	-3.482
9.926	4.509	10.074	-3.991
14.929	5.473	15.071	-4.799
19.936	6.206	20.064	-5.410
24.945	6.761	25.055	-5.865
29.955	7.161	30.045	-6.189
34.966	7.418	35.034	-6.388
39.978	7.534	40.022	-6.462
44.989	7.480	45.011	-6.384
50.000	7.242	50.000	-6.138
55.010	6.820	54.990	-5.724
60.018	6.244	59.982	-5.176
65.025	5.558	64.975	-4.528
70.029	4.779	69.971	-3.807
75.031	3.942	74.969	-3.046
80.029	3.065	79.971	-2.269
85.025	2.182	84.975	-1.508
90.019	1.327	89.981	-.809
95.009	.557	94.991	-.241
100.000	0	100.000	0

L.E. radius: 1.311
Slope of radius through L.E.: 0.0421

TABLE II

ORDINATES OF AN INTERMEDIATE AIRFOIL SECTION

[Stations and ordinates given in percent of airfoil chord. Ordinates measured from wing reference line]

Upper Surface		Lower Surface	
Station	Ordinate	Station	Ordinate
0	.450	0	.450
.533	1.571	.404	-.404
.796	1.779	.592	-.567
1.358	2.129	1.017	-.850
2.792	2.767	1.942	-1.321
5.825	3.775	3.700	-1.929
8.908	4.546	5.488	-2.433
11.988	5.167	7.304	-2.871
17.867	6.088	11.067	-3.617
23.413	6.700	14.867	-4.225
28.783	7.104	18.896	-4.742
33.792	7.329	23.313	-5.188
38.600	7.404	28.283	-5.567
43.533	7.346	33.983	-5.850
48.583	7.117	40.271	-5.963
53.783	6.700	46.700	-5.888
56.583	6.358	52.454	-5.621
59.425	5.979	57.700	-5.225
62.263	5.546	62.775	-4.746
65.079	5.067	68.296	-4.142
70.063	4.213	74.329	-3.442
75.046	3.283	77.425	-3.071
80.038	2.333	79.946	-2.767
85.025	1.358	84.963	-2.171
90.008	.421	89.967	-1.629
94.996	-.433	94.983	-1.200
99.988	-1.054	99.988	-1.054

L.E. radius: 1.193
Slope of radius through L.E.: 0.423

TABLE III

ORDINATES OF THE NACA 65_1-212, a = 0.6
AIRFOIL (TIP SECTION)

[Stations and ordinates given in percent of airfoil chord. Ordinates measured from airfoil chord line]

Upper Surface		Lower Surface	
Station	Ordinate	Station	Ordinate
0	0	0	0
.399	.982	.601	-.852
.638	1.194	.862	-1.012
1.124	1.520	1.376	-1.242
2.356	2.113	2.644	-1.625
4.837	3.017	5.163	-2.185
7.329	3.728	7.671	-2.606
9.827	4.330	10.173	-2.956
14.833	5.290	15.167	-3.492
19.848	6.042	20.152	-3.904
24.869	6.611	25.131	-4.197
29.893	7.029	30.107	-4.401
34.921	7.304	35.079	-4.518
39.951	7.444	40.049	-4.550
44.983	7.423	45.017	-4.475
50.017	7.231	49.983	-4.283
55.051	6.856	54.949	-3.968
60.094	6.319	59.906	-3.567
65.123	5.634	64.877	-3.124
70.124	4.842	69.876	-2.640
75.112	3.983	74.888	-2.131
80.090	3.082	79.910	-1.604
85.064	2.173	84.936	-1.085
90.036	1.297	89.964	-.595
95.013	.521	94.987	-.191
100.000	0	100.000	0

L.E. radius: 1.000
Slope of radius through L.E.: 0.1097

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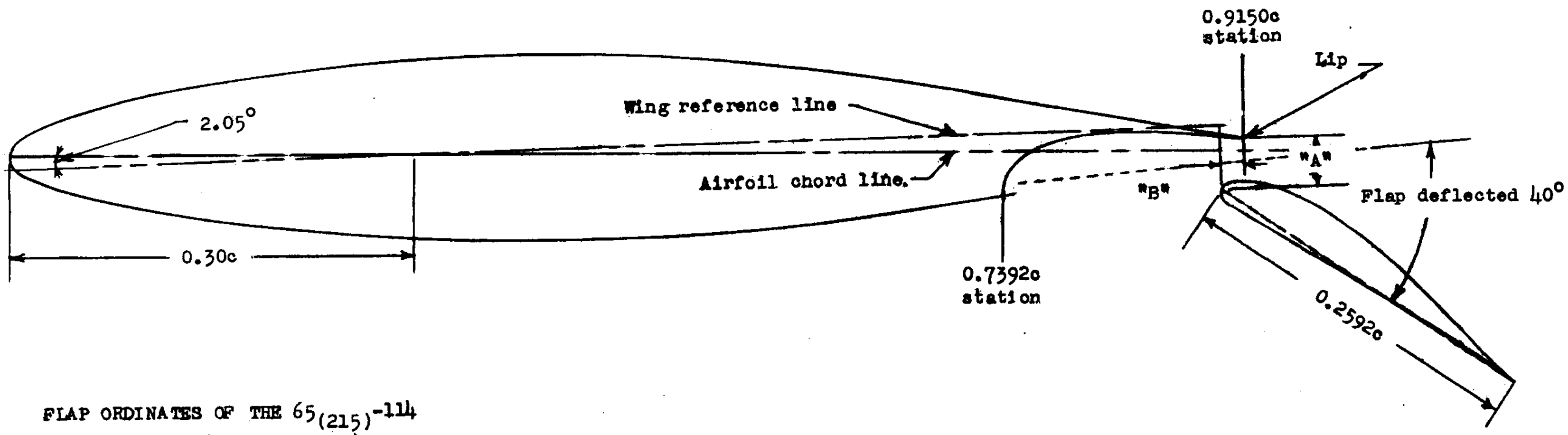

FLAP ORDINATES OF THE $65_{(215)}$-114
AIRFOIL (ROOT SECTION)

[Stations and ordinates given in percent of flap chord]

Station	Upper surface	Lower surface
0	0	0
1.25	3.06	-2.41
2.50	4.02	-2.89
5.00	5.71	-2.81
7.5	6.99	-2.65
10	8.04	-2.49
15	9.57	-2.17
20	10.45	-1.85
30	11.18	-1.21
40	10.93	-.56
50	9.89	-.08
60	8.28	.40
70	6.27	.72
80	4.10	.88
90	1.85	.56
100	0	0
L.E. radius: 3.46		

FLAP NOSE POSITIONS

[Dimensions "A" and "B" given in percent of airfoil chord]

Position(deg)	"A"	"B"
Full up	2.77	17.35
4 (cruise)	2.42	13.48
0	5.07	2.26
10	4.85	2.55
20	4.56	2.57
27.5	4.29	2.43
30	4.23	2.36
40	3.83	1.88
50	3.43	1.11

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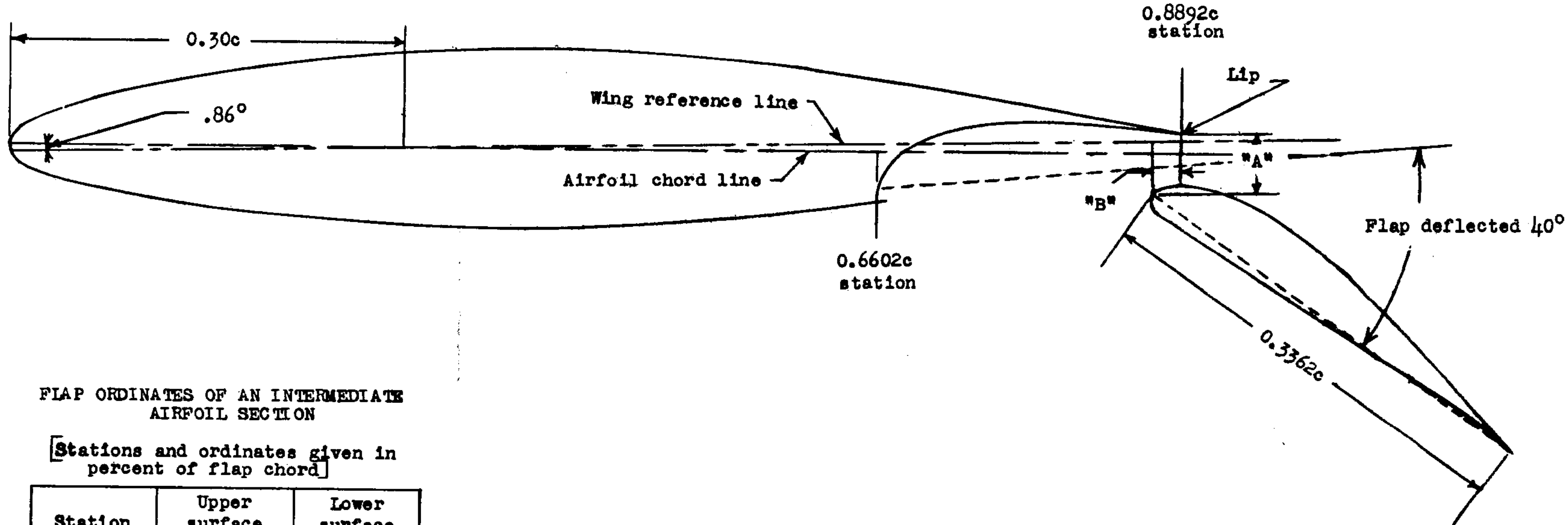
Figure 1 .- Drawing of the NACA $65_{(215)}$-114 airfoil (root section) for the Chance-Vought XF6U-1 airplane giving the positions and dimensions of the slotted flap.



FLAP ORDINATES OF AN INTERMEDIATE AIRFOIL SECTION

[Stations and ordinates given in percent of flap chord]

Station	Upper surface	Lower surface
0	0	0
1.25	2.72	-2.52
2.50	3.84	-2.97
5.00	5.69	-3.09
7.50	7.07	-2.85
10	8.04	-2.85
15	9.65	-2.60
20	10.64	-2.35
30	11.39	-1.73
40	11.14	-1.24
50	9.90	-.74
60	8.29	-.25
70	6.31	.25
80	4.21	.50
90	1.86	.37
100	0	0
L.E. radius: 3.08		

FLAP NOSE POSITIONS

[Dimensions "A" and "B" given in percent of airfoil chord]

Position(deg)	"A"	"B"
Full up	3.83	22.52
4 (cruise)	3.25	17.44
0	6.64	3.65
10	6.16	3.72
20	5.64	3.45
27.5	5.25	2.98
30	5.17	2.84
40	4.60	1.86
50	4.09	0.53

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Figure 2 .- Drawing of an intermediate airfoil section for the Chance-Vought XF6U-1 airplane giving the positions and dimensions of the slotted flap.

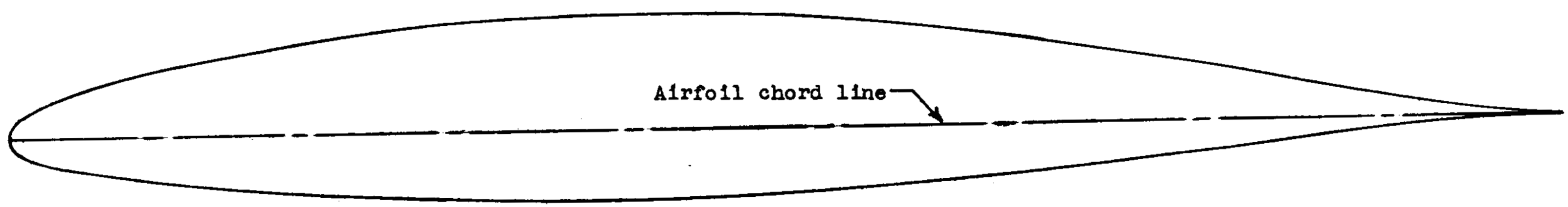

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Figure 3 .- Drawing of the NACA 65_1-212, a = .6 airfoil (tip section) for the Chance-Vought XF6U-1 airplane.

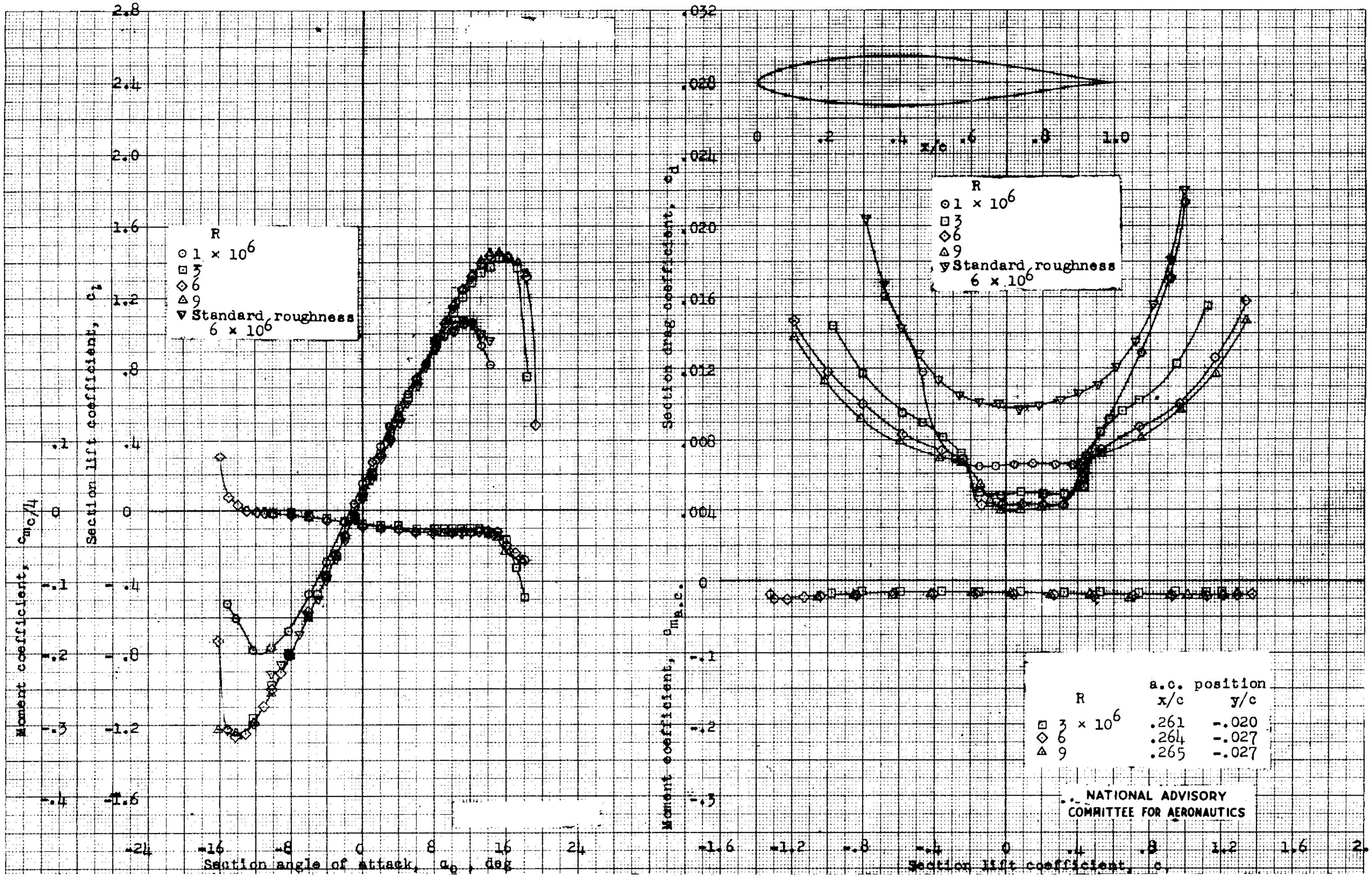

Figure 4.- Aerodynamic characteristics of the NACA $65_{(215)}$-114 airfoil (root section) equipped with a slotted flap for the Chance-Vought XF6U-1 airplane, flap retracted. Tests, TDT 880 and LTT 418.

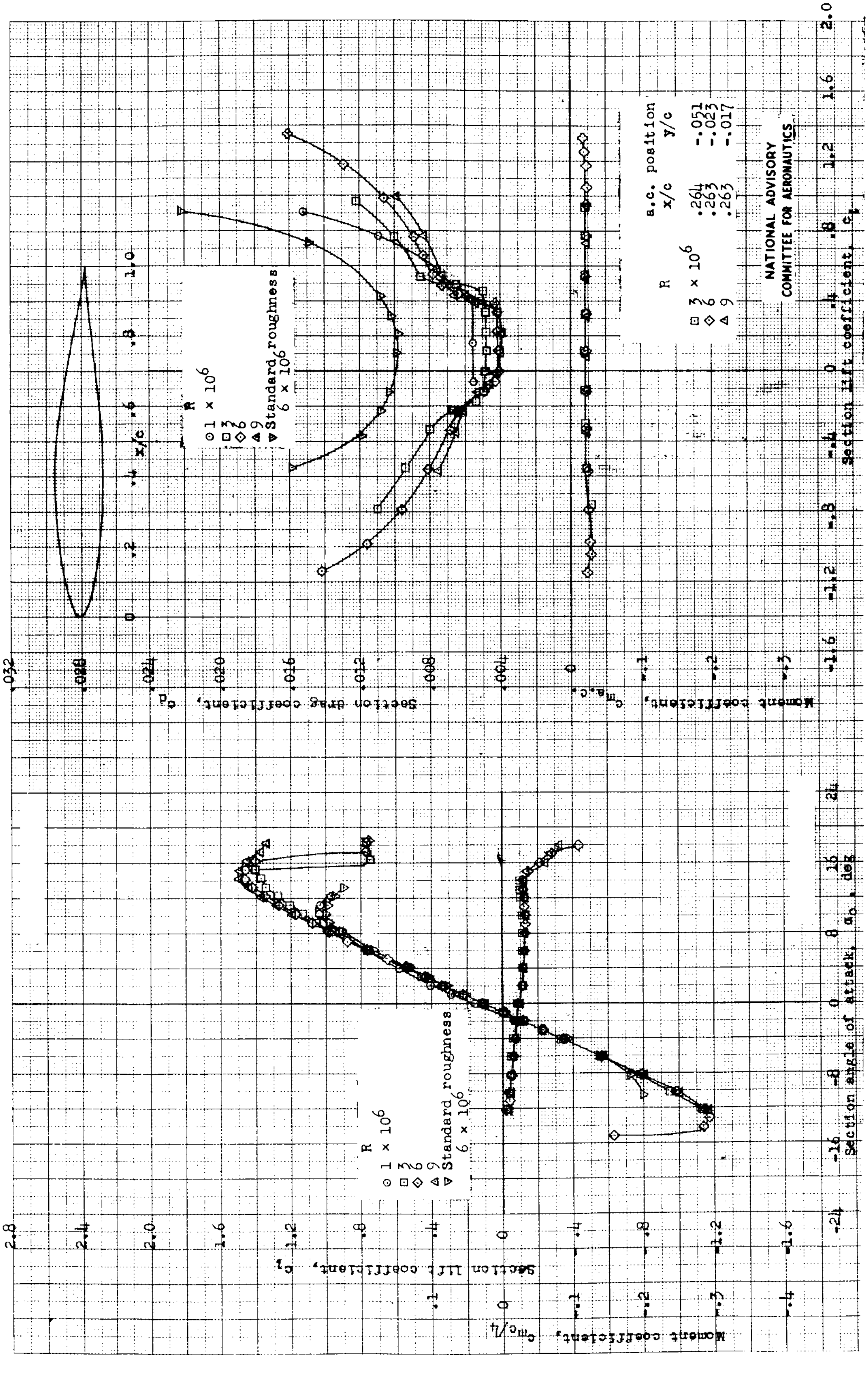

Figure 5.- Aerodynamic characteristics of an intermediate airfoil section equipped with a slotted flap for the Chance-Vought XF6U-1 airplane, flap retracted. Tests, TDT 383 and LTT 418.

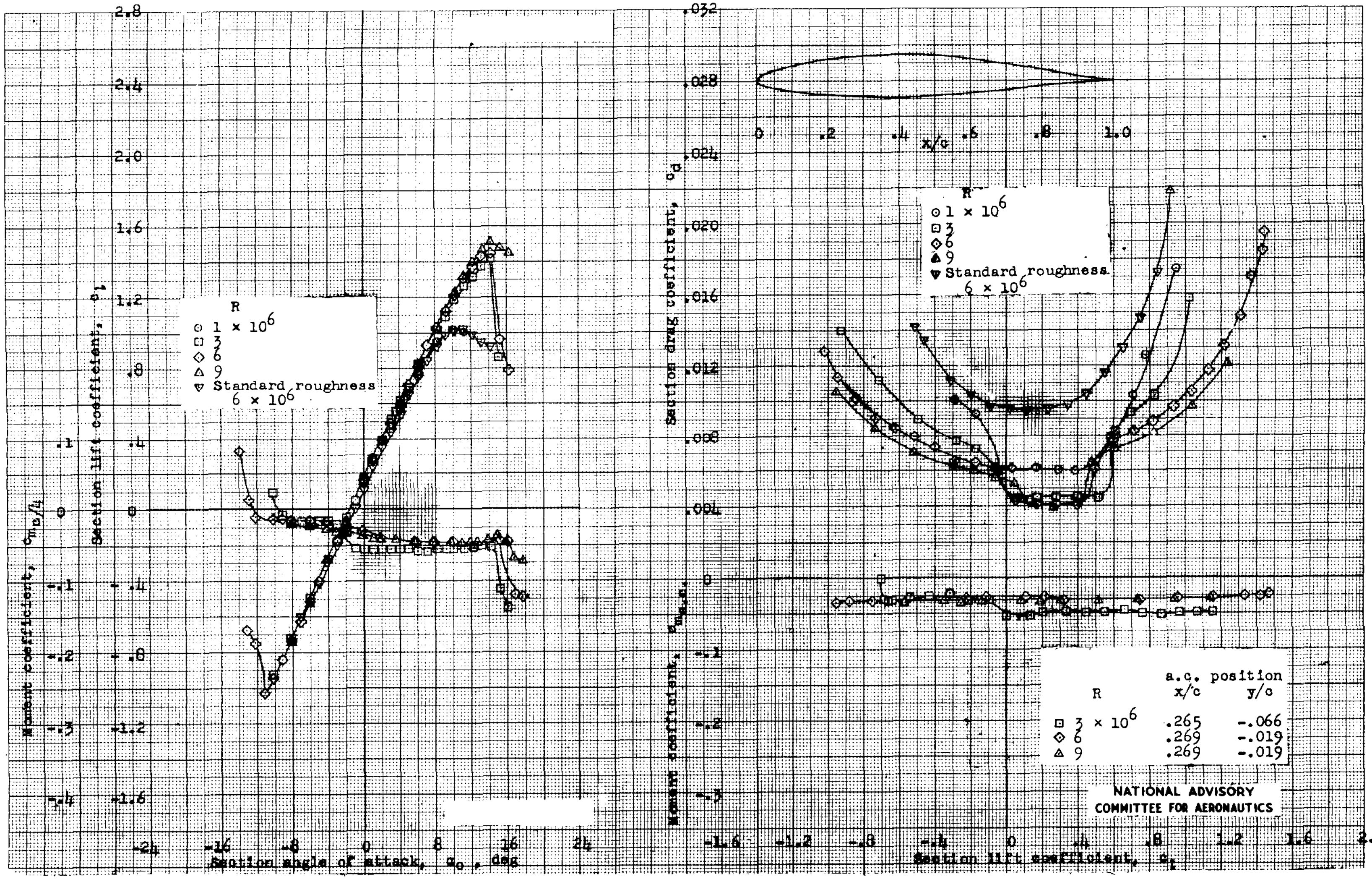

Figure 6.- Aerodynamic characteristics of the NACA 65_1-212, a = .6 airfoil (tip section) for the Chance-Vought XF6U-1 airplane. Tests, TDT 886 and LTT 420.

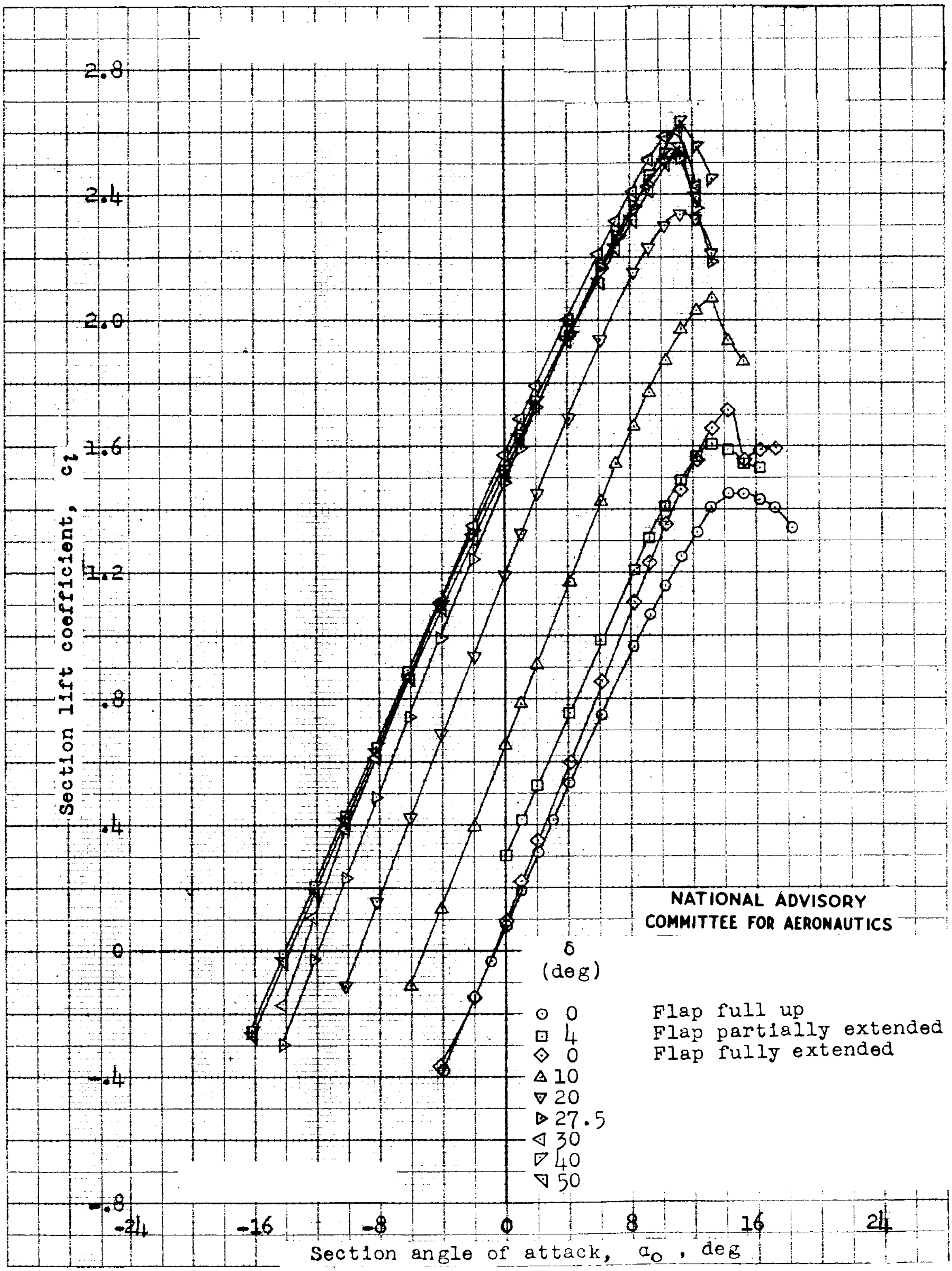

Figure 7.– Lift characteristics at various flap deflections of a root airfoil section equipped with a slotted flap for the Chance–Vought XF6U–1 airplane. $R_e = 9 \times 10^6$; test, TDT 914.

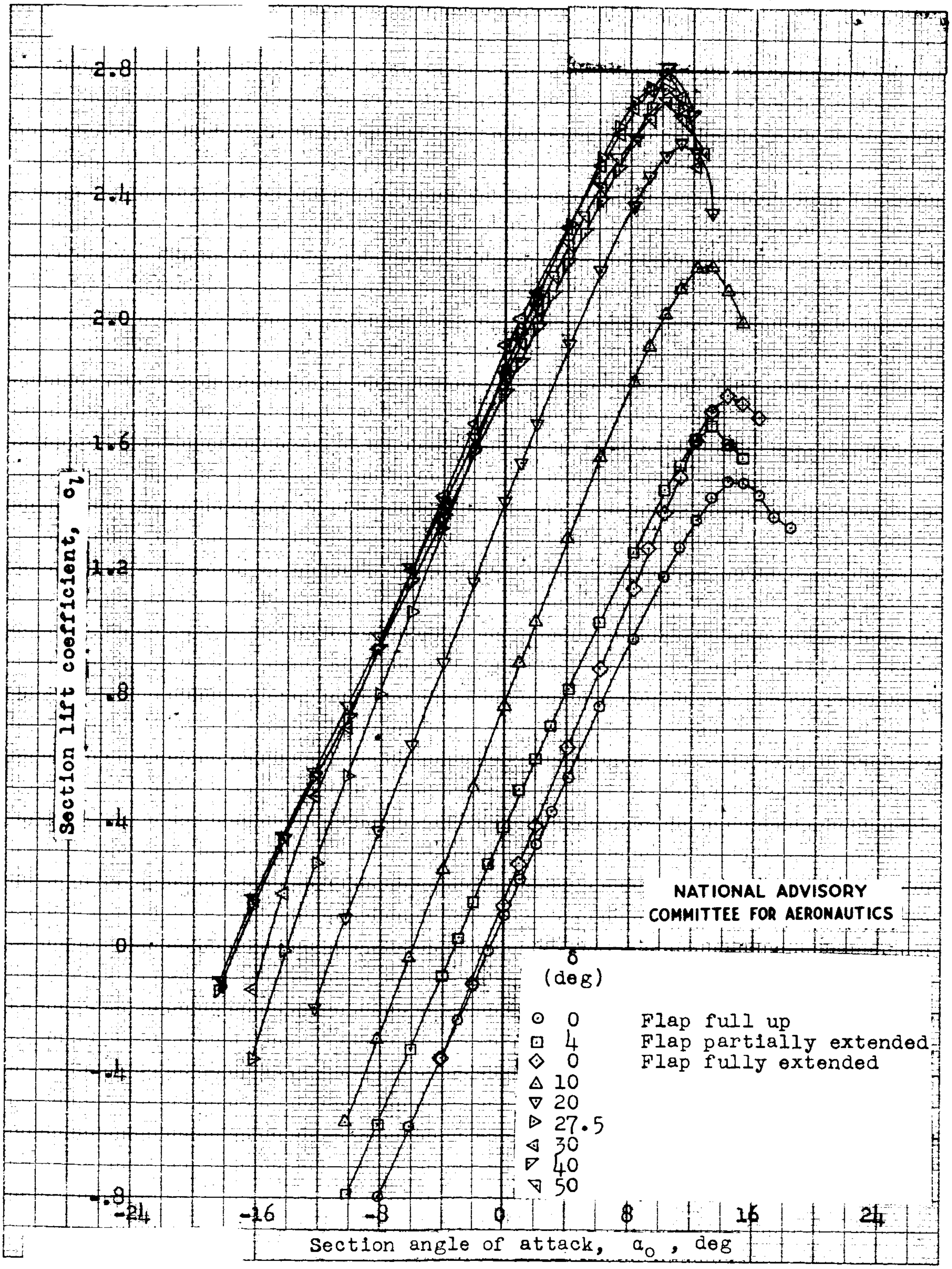

Figure 8.- Lift characteristics at various flap deflections of the NACA $65_{(215)}$-114 airfoil (intermediate section) equipped with a slotted flap for the Chance-Vought XF6U-1 airplane. $R = 9 \times 10^6$; test, TDT 915.

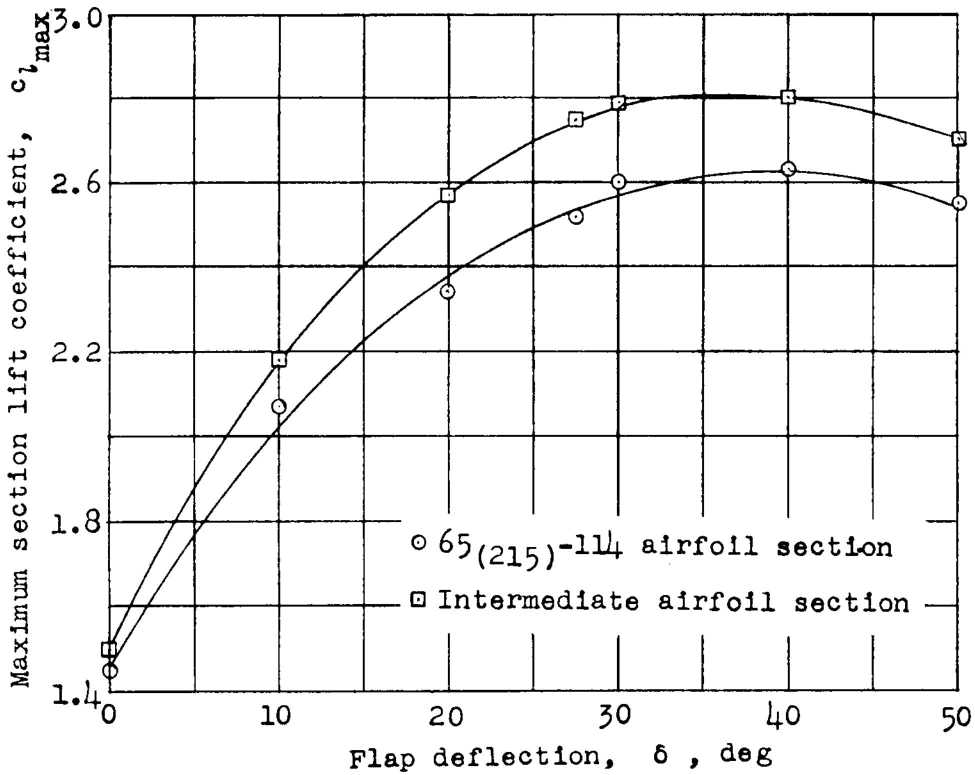

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Figure 9.- Variation of maximum section lift coefficient with flap deflection for the NACA $65_{(215)}$-114 airfoil (root section) and an intermediate airfoil section, both equipped with a slotted flap, for the Chance-Vought XF6U-1 airplane. Tests, TDT 914 and 915.

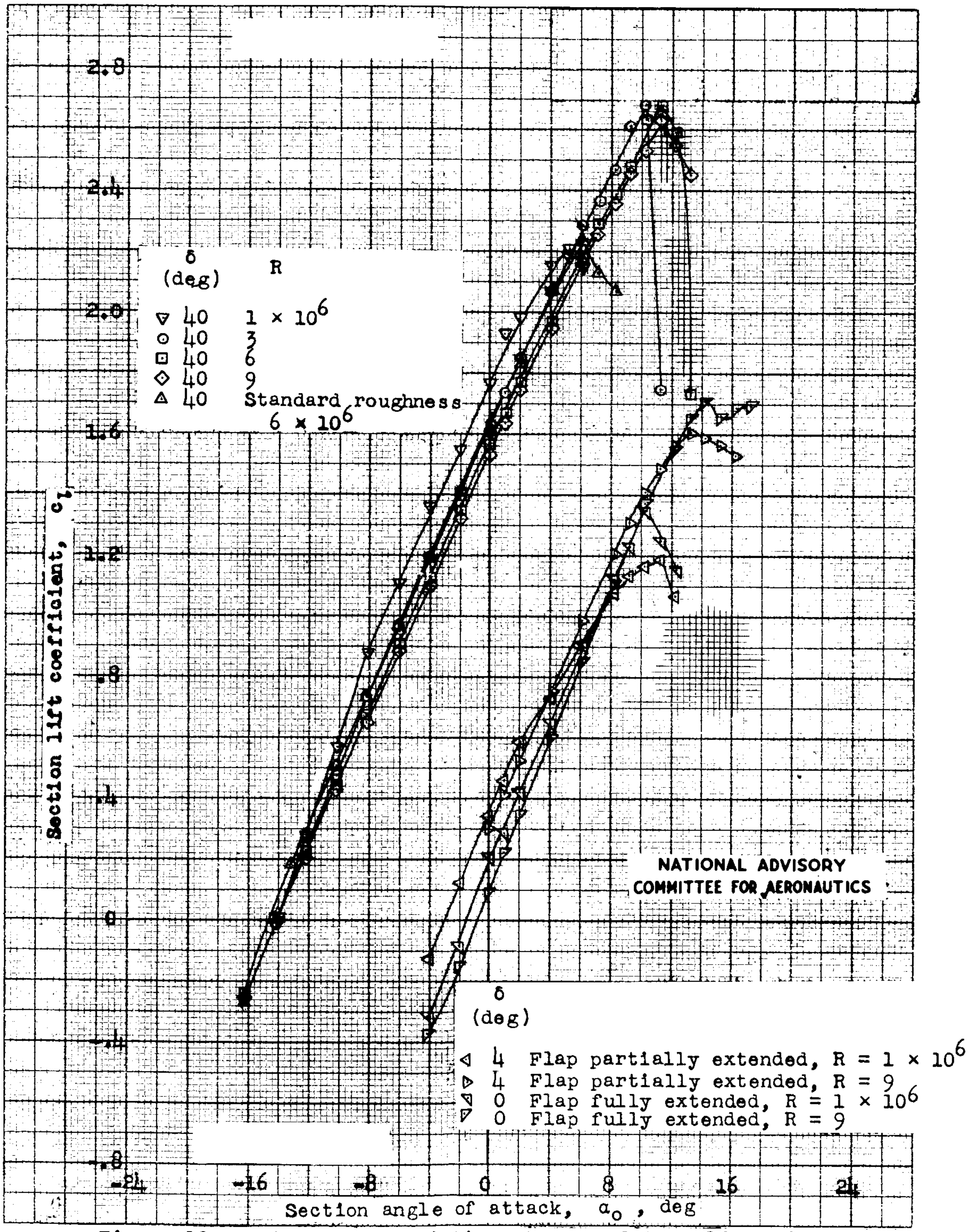

Figure 10.- Lift characteristics at several Reynolds numbers and flap deflections of the NACA $65_{(215)}$-114 airfoil (root section) equipped with a slotted flap for the Chance-Vought XF6U-1 airplane. Tests, TDT 915 and LTT 418.

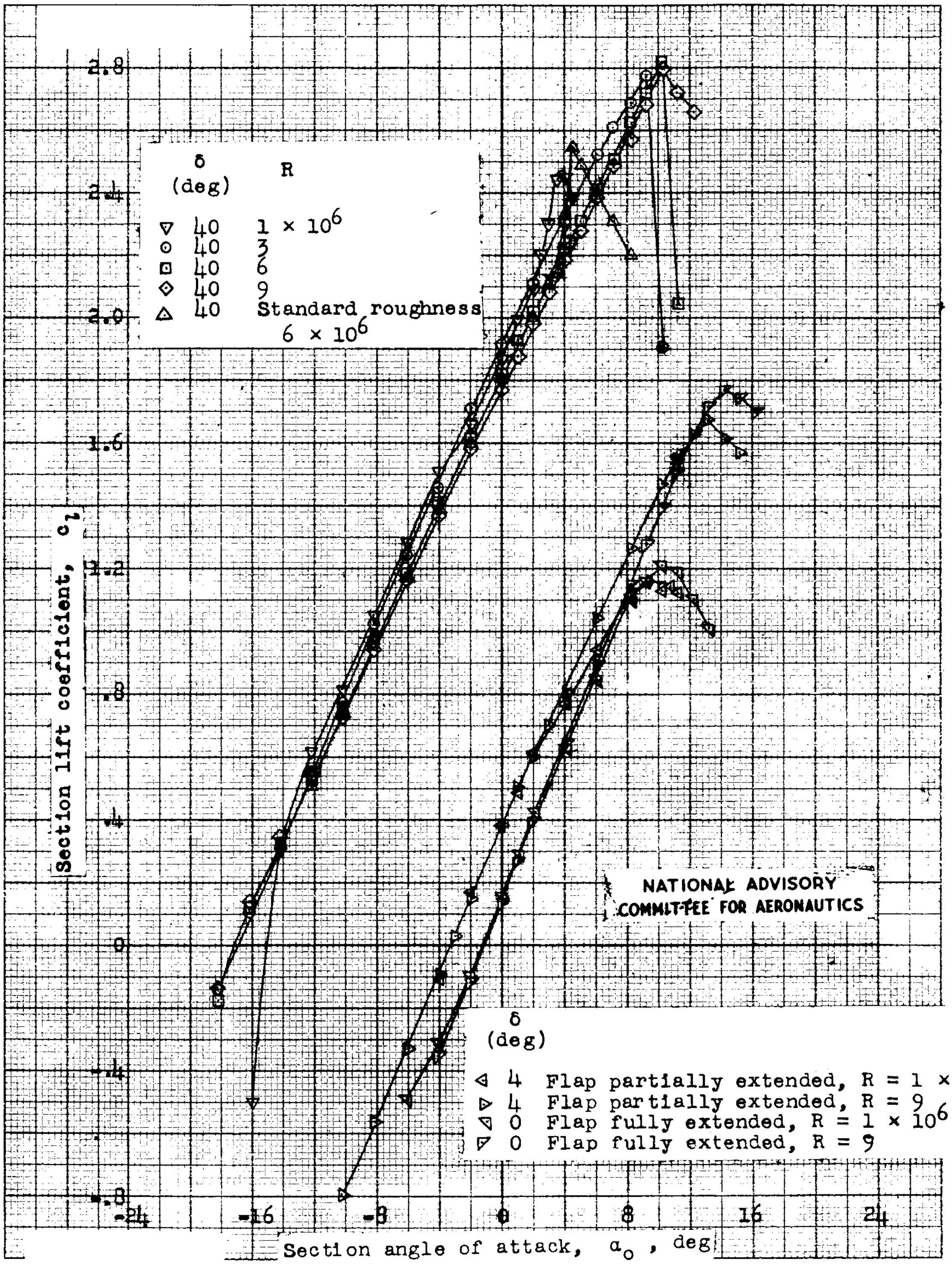

Figure 11.- Lift characteristics at several Reynolds numbers and flap deflections of an intermediate airfoil section equipped with a slotted flap for the Chance-Vought XF6U-1 airplane. Tests, TDT 914 and LTT 419.

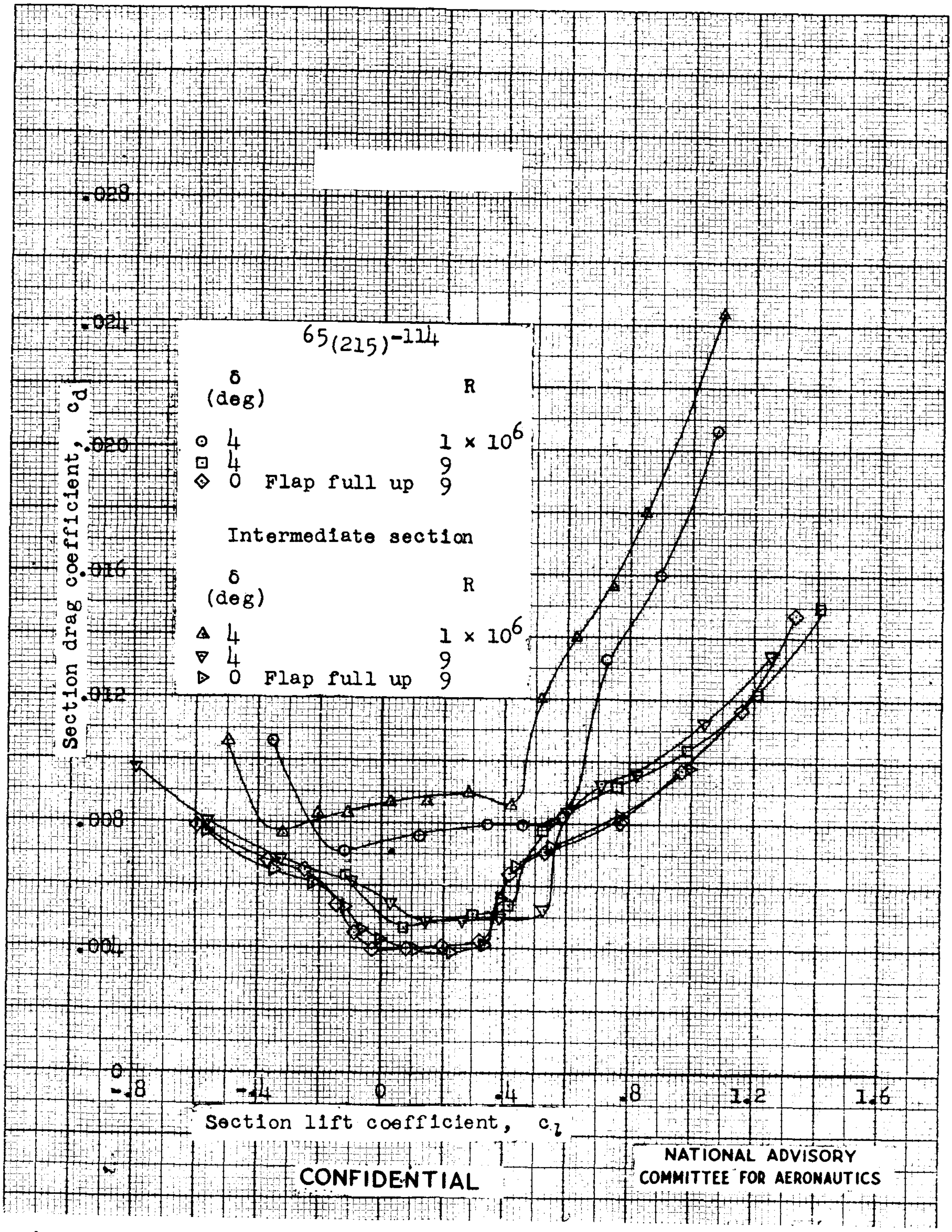

Figure 12.- Drag characteristics of two configurations of the NACA $65_{(215)}$-114 airfoil (root section) and an intermediate airfoil section, both equipped with a slotted flap, for the Chance-Vought XF6U-1 airplane. Tests, TDT 914 and 915, and LTT 417 and 418.

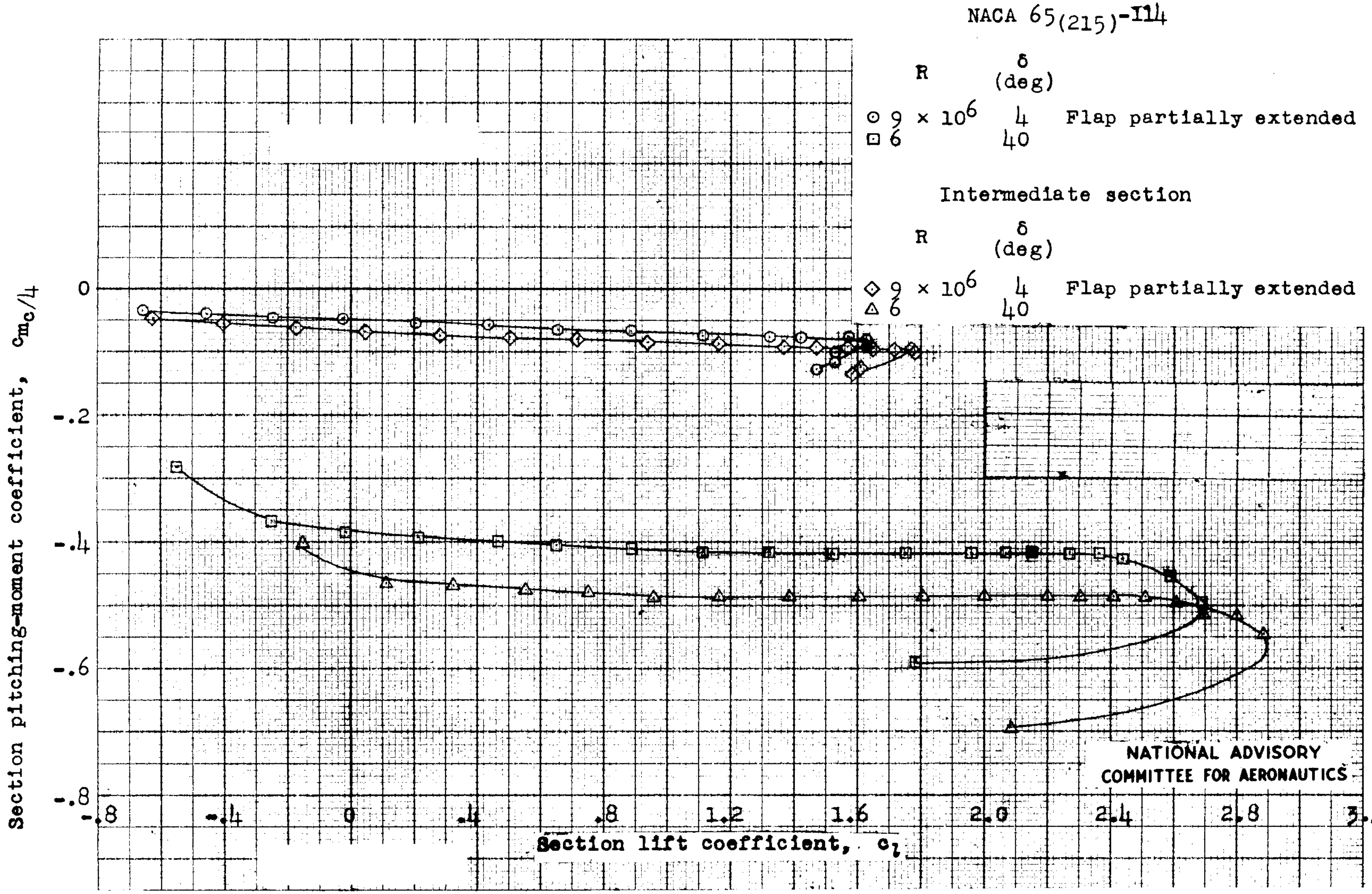

Figure 13.- Pitching-moment characteristics at two flap deflections of the NACA $65_{(215)}$-114 airfoil (root section) and an intermediate airfoil section, both equipped with a slotted flap, for the Chance-Vought XF6U-1 airplane. Tests, TDT 914 and 915.